Shock Breakout Explorer

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Abstract: The death of massive stars, manifested as core-collapse supernovae (CCSNe), critically influence how the universe evolves. Despite their fundamental importance, our understanding of these enigmatic objects is severely limited. We have performed a concept study of a space-based transient observatory that will rapidly facilitate an expansion of our understanding of these objects. By combining a very wide-field X-ray telescope with an ultraviolet telescope, and a rapidly slewing spacecraft we can constrain the poorly understood explosion mechanism of massive stars. This goal is met by observing the shock breakout (SBO) of CCSNe to measure the outer envelope parameters of massive stars. A description of the observatory, mission simulation, and technology used is provided.

Introduction: The death of massive stars is a fundamental process in shaping our universe. The first massive stars are considered a significant contributor to reionization and the dispersal of the first metals. Later generations continue the production and dissemination of heavy elements, which shape planets, solar systems, future generations of stars, and galaxies. Despite their importance, how massive stars end their lives, is not well-understood. To unlock our understanding of these enigmatic objects, we have performed a concept study of a SBO Explorer (SBE) to enable the earliest time studies of massive star SBOs.

SBE accomplishes this by combining a very wide-field X-ray telescope (WFXT; see Figure 1) for triggering and X-ray follow up; a multi-mode UV instrument (MUVI; 115–350 nm; see Figure 3) for imaging and spectroscopy (R~3,000); with a rapidly-slewing spacecraft (S/C; see Figure 2). The WFXT is used for localizing SBO events from CCSNe. When a new target is found by the WFXT, the MUVI field-of-view is centered on the target. Data are in imaging mode for MUVI. The MUVI centers the UV spectrograph on the location determined from the MUVI image.

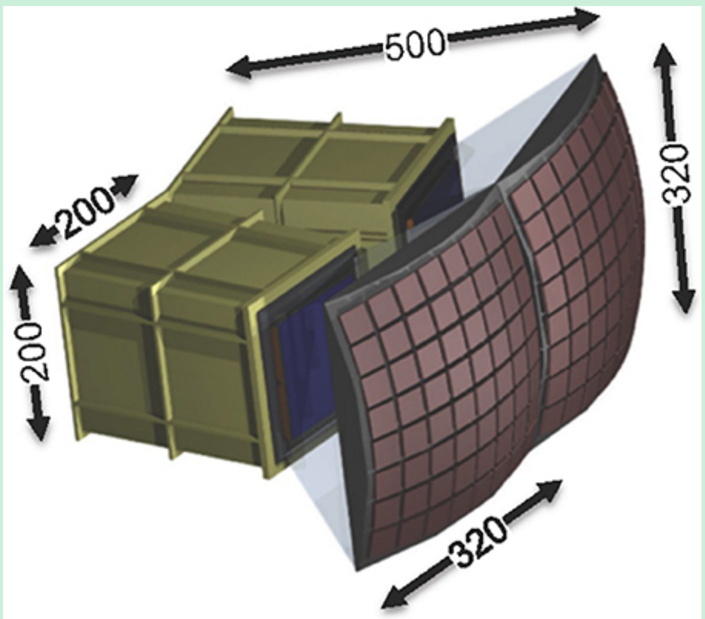

Figure 1. Two of four SBE-WFXT modules for localizing SBO events of CCSNe. Dimensions provided are in mm.

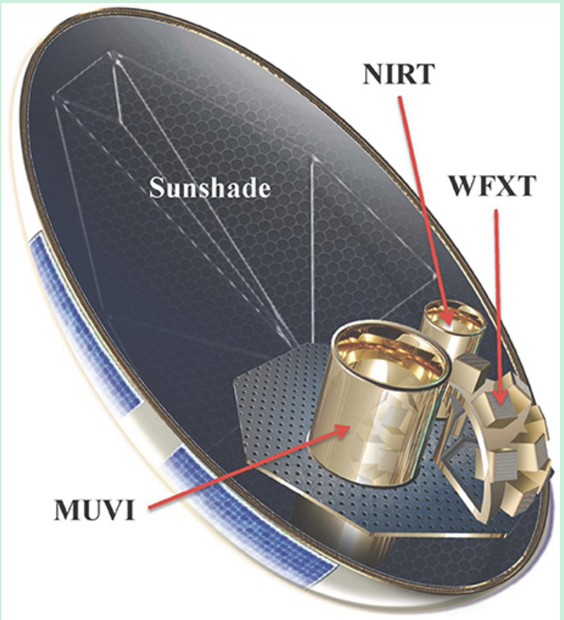

Figure 2. SBE S/C concept would not include a NIRT, fewer WFXT modules, and a smaller sunshade.

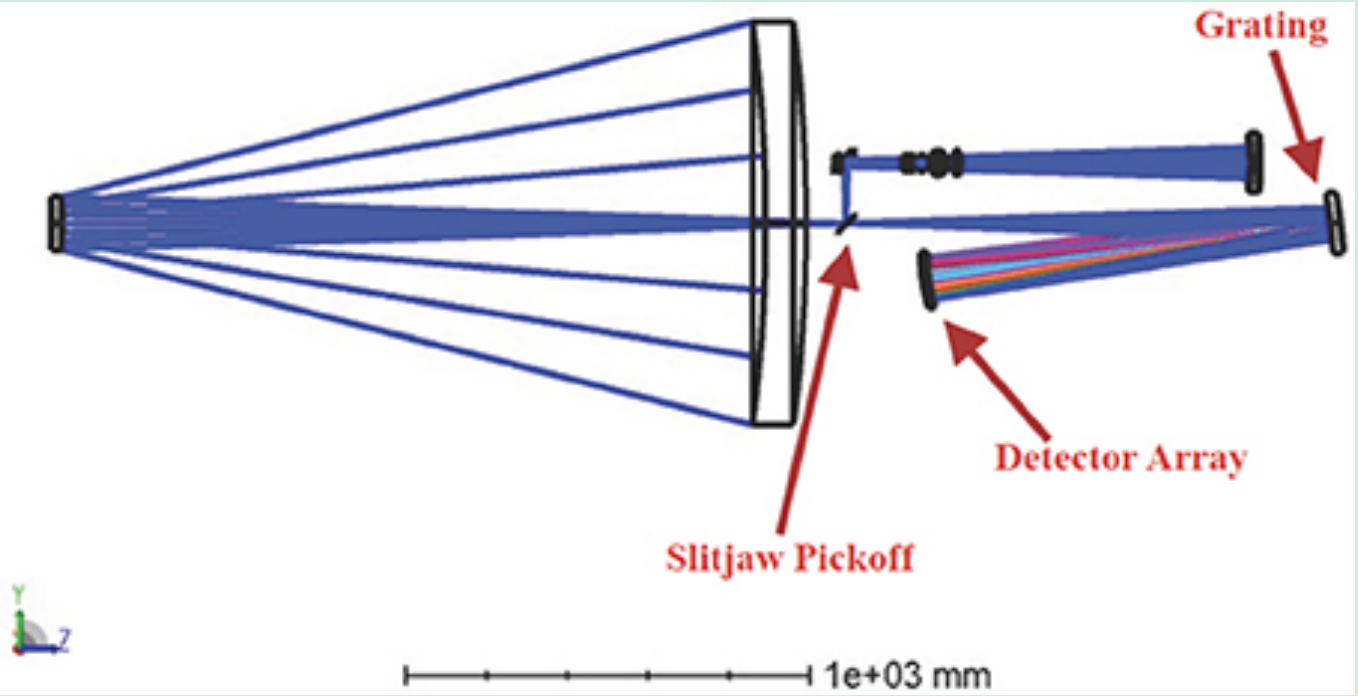

Figure 3. MUVI telescope, spectrograph, and imager design. This design offers high throughput while maintaining low-resolution spectroscopy and approximately arcsecond-level imaging for SN localization, galactic characterization, and light curve follow-up.

Mission Science Goals: When a CCSNe explodes, it pushes a shock wave through the star until it reaches the outer layers. At the point of SBO the outer layers of the star radiate as a hot pseudo-blackbody, with a peak flux in the far-UV or soft X-ray energy range. As the star expands, the escaping emission comes from progressively deeper layers. By the time the SN expands enough for its optical light to be detected, much information about the progenitor star and its environment conditions are lost. Because of high opacities from iron-peak elements, UV light observed in SNe come from a much higher level in the ejecta. Observing the earliest UV light from SNe contains important information on progenitor star sizes and compositions. Tying specific progenitor stars to the resultant explosions is an important goal of stellar evolution studies.

Figure 4 shows broadband light curves for a range of Type II SN using a one-temperature light-curve code (de la Rosa et al., 2016). In these models, we vary a wide range of SN characteristics. With just the light-curve from the primary peak, it is often difficult to distinguish the dominant characteristics. Spectra at late times can provide some information, particularly about the kinetic energy of the explosion. But the breakout emission provides crucial additional constraints, especially on the density profile, stellar radius, and progenitor size. However, with only one breakout observation from a "normal" SN, astronomers have not been able to take advantage of this constraint. By increasing this number many-fold, this diagnostic will revolutionize our understanding of SNe.

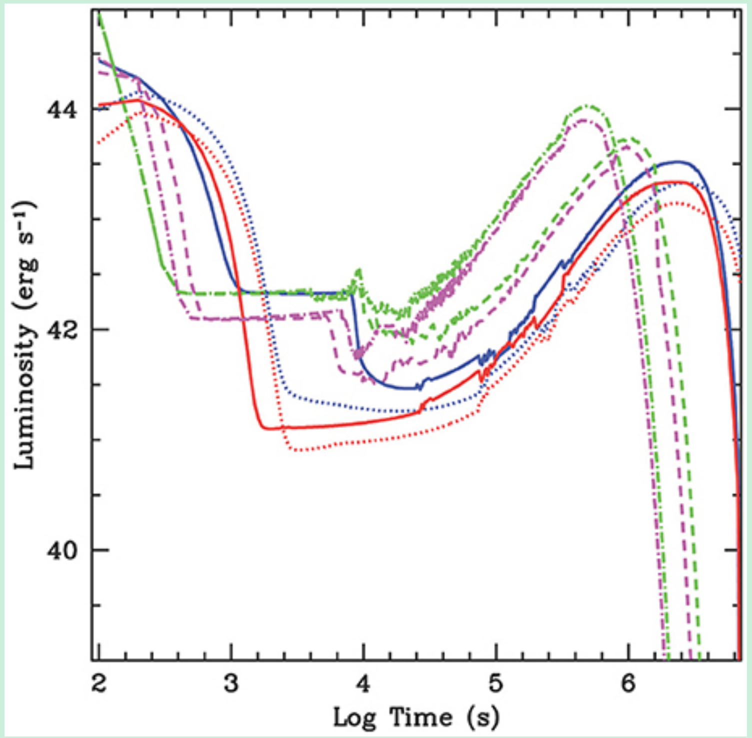

Figure 4. 115–180 nm light curves for a range of SN explosions. In the models, we vary initial stellar radius (red & magenta = 10^{12} cm, blue & green = 10^{13} cm), ejecta mass (dotted = $8M_{\odot}$, all others = $4M_{\odot}$), explosion energy (dot-dashed = 6×10^{51} erg, all others = 10^{51} erg), and density profile ($\rho = r^{-\alpha}$; dashed for α = 2.5, all others for α = 0). All these factors alter light-curves and with limited data from the primary peak, it is difficult to distinguish these. SBE would disentangle these differences.

Although some basic trends exist between photospheric radius and breakout peak duration, these results depend upon a number of assumptions about the shock structure (temperature, density) and nature of the emission (thermal vs. nonthermal). Observations in both X-ray and UV, allow us to constrain the SN engine. Figure 5 illustrates X-ray and UV lightcurves, assuming thermal emission and fully ionized atoms where electron scattering dominates the opacity. MUVI spectroscopic observations will also provide constraints on the metallicity.

Mission Simulations: To predict SBE SBO rates, we carried out a rigorous simulation of the WFXT performance. The SBO simulation uses the SN rate of Strolger et al. (2015) to determine the number of CCSNe available in a 5-year period. Each SN is assigned to a galaxy. The galaxy distribution is determined from the Galaxy Catalog of White et al. (2011), which is complete to 100 Mpc. Using this catalog, we extrapolate the number of galaxies out to 500 Mpc. There is a fall off in the number of detectable sources after 500 Mpc, but we should still detect WR SNe out to 1,000 Mpc. The extrapolated galaxies past 100 Mpc are given a random RA, DEC, and distance. The SNe are then assigned a type and weighted according to Strolger et al. (2015) and Smartt (2009): RSG (59.7%), BSG (1%), WR (31.34%), or Other (e.g., IIn's; 7.96%).

Each SN was then assigned an X-ray peak luminosity (L_X), peak time (t_{peak}), and light curve shape, based on the SBE team's and Nakar and Sari (2010) models, and constrained to a narrow distribution based on the X-ray SNe 2006aj (Campana et al., 2006) and 2008D (Soderberg et al., 2008; Modjaz et al., 2009). We also assign a random N_H to each SN based on the distribution in Willingale et al. (2010). The SN luminosity is converted into brightness after attenuation for distance and N_H. We then determine if and for how long the SN is visible in the X-ray based on the sensitivity of the WFXT.

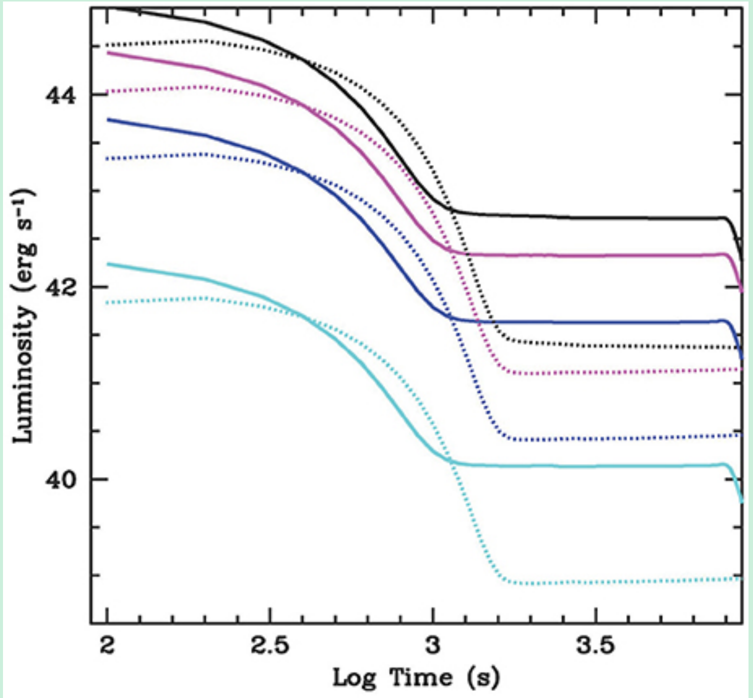

Figure 5. X-ray (black), 115–180 nm (magenta), 200–350 nm (blue), and V-band (cyan) early luminosities as a function of time for two SN explosions whose only difference lie in their radii: 10^{12} cm (dotted), 10^{13} cm (solid). SBE would easily capture this early emission and not only distinguish different radii, but pin down breakout temperatures, which are important for understanding the entire lightcurve.

Each SN was then assigned a UV luminosity (L_{UV}), t_{peak}, and light curve shape, based on the SBE team's and Nakar and Sari (2010) models, and constrained by *Swift* UVOT (Roming et al., 2005) observations of CCSNe (Brown et al., 2014; Pritchard et al., 2014). The L_{UV} is then converted into brightness after attenuation for extinction and distance. To calculate extinction, N_H is converted into an E(B-V) value according to the convention of Predehl and Schmitt (1995) and then the total extinction determined using Cardelli et al. (1989), assuming an R_V = 2.72 as a worst-case scenario. We then determine if the SN is visible and for how long in the UV using MUVI's sensitivity.

Table 1 shows a projected detection of 97 SBO events over an SBE five-year mission period. This projection was calculated from the WFXT sensitivity, bandpass, and FOV, convolved with a model of CCSNe based on *Swift* data. As a comparison, over a 12-year period, *Swift* has detected only two SBO events in X-rays, a critical wavelength for uncovering these events. In addition, only a handful of UV/optical flashes from SBO events have been detected by the Galaxy Evolution Explorer (Gezari et al., 2008) and *Kepler* (Garnavich et al., 2016).

Progenitor	No. of SBOs
Wolf-Rayet (WR)	22
Blue Supergiant (BSG)	2
Red Supergiant (RSG)	63
Other	10
Total	**97**

Conclusion: The motivation behind the SBE concept is to significantly expand our understanding of the death of massive stars, which are key to our understanding of many other aspects of astrophysics. Other observatories (e.g. *Chandra*, NuSTAR, *Swift*, HST, and *Kepler*) have explored components in the death of massive stars, but no past, current, or planned mission has the capability to move our understanding of CCSNe SBO from discovery to exploration. The SBE is designed to progress our understanding of these massive objects into the next phase.

More details of a SBE concept can be found at https://www.frontiersin.org/articles/10.3389/fspas.2018.00025/full#B70